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Interactive comment on "*Review article* "Air-sea exchanges of CO_2 in world's coastal seas"" *by* C.-T. A. Chen et al.

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We appreciated the through and constructive comments which helped strengthening the manuscript.

General Comments: This paper synthesized the CO_2 fluxes in the world's estuaries and continental shelves, with new available data in various places. The paper is a good update on what we know about the CO_2 fluxes in these coastal systems. It should have a good impact in coastal carbon research. The paper is reasonably well written, but a careful checkup on the language is necessary. There are a few points I want to make about the paper.

Reply: Thanks for reminding.

The paper is lack of a method/data analysis section. Although this is a review paper, I think it is useful and important to see how the data were analyzed and upscaled to derive the global estuary and shelf CO_2 fluxes. I don't see this was well presented in the paper. Related to the last point, it may be better to use different upscale methods to come up with a range of CO_2 fluxes. As authors pointed out, the coastal ocean CO_2 fluxes are highly variable in space and time. We don't have a good handle on how we should upscale the sparse data. Using different methods will help to see what might be the uncertainty these flux estimate may have. It is also useful to see how the areas without data coverage are treated. Again, different ways of treatment may have different effects on the final estimate, which is worth discussion.

Reply: We have now added the method of calculating pCO_2 flux (new Table 2) and the global flux as follows:

"Numerical data are gathered for 165 estuaries (Table 1), of which 99 are from literature. Unpublished data from 50 estuaries and 16 from data banks are also included, and the Wanninkhof (1992) quadratic equation is used to determine the flux. The method used to calculate the flux, as well as sources of the gas exchange coefficient and wind speed are listed in Table 2. Of note is that using different pCO_2 flux method and gas transfer velocity causes disparity in flux estimations (Borges et al., 2004; Ferron et al., 2007; Jiang et al., 2008a; Zappa et al., 2007). However, there is still not a consensus on the most suitable coefficient to use in estuaries. Factors affecting gas exchange coefficients include wind speed, tidal current and bottom stress, whereas the wind speed is the most considered. It is important to point out that this paper deals mostly with published results. It is not possible to re-do the flux calculations, say, based on the same gas exchange coefficient, as the original data were not provided in the papers cited. Important to note is that there is a lack of temporal coverage in most of the data sets although previous studies (Bozec et al., 2011;

Dai et al., 2009; Kitidis et al., 2012) have demonstrated short term changes in pCO_2 at scales of days or less. Yet, typically data on such a scale are limited to only a few cruises. The lack of seasonality in the numerically averaged fluxes is almost certainly an artefact influenced by averaging all available data."

"In the above calculation, the areas of groups of estuaries are taken from the most recent and comprehensive work of Laruelle et al. (2013), which divided the world into regions and calculated a total estuarine area of $1.012 \times 10^6 km^2$, slightly smaller than the value of $1.067 \times 10^6 km^2$ given in Laruelle et al. (2010). Table 3 lists the total surface area in each of the 45 regions and the numerically averaged CO_2 flux per unit area for each region. Our global flux calculation is based on the sum of regional fluxes for these 45 zones (area multiplied by zonal average CO_2 flux $(molCm^{-2}\ yr^{-1})$). These 165 estuaries are compartmentalized into 35 regions, and the numerically averaged CO_2 flux per unit area is calculated. For 10 regions without data, the mean flux for the same classification region is used (Table 3). The outgassing of pCO_2 in global estuaries is $0.094 PgC\ yr^{-1}$, and is about 31% of the global riverine organic carbon flux (Seitzinger et al., 2010). This compares with the 48% of organic carbon released as CO_2 from estuaries and inland waters (Tranvik et al., 2009)."

When we choose the equation of gas transfer velocity, we only follow the same equation most authors use in our cited literature. Wanninkhof (1992) is the most used, followed by different equations of Raymond and Cole (2001). For the CO_2 flux in global estuaries, our Asian calculation constitutes 7% of surface area and 13% of CO_2 flux in global estuaries. Therefore, most part of global estimation is based on published articles. In this study, we try to emphasize that the high wind speed will result in high CO_2 flux. We have revised the paragraphs as follows:

The 50 newly considered estuaries in Taiwan, southern China and Southeast Asia, all at low latitudes, have lower fluxes than determined from previously

obtained results (Table 1), which include many data for European rivers. For instance, only two of the 19 estuaries that were considered by Abril and Borges (2005), who published perhaps the first global study of CO_2 emissions from estuaries, are outside Europe and the eastern seaboard of the USA. Those authors found a global CO_2 flux per unit area of $35.7 molCm^{-2}\ yr^{-1}$, which is more than triple the value obtained in this study. This finding does not imply that European rivers have higher pCO_2: they do not. Rather, Europe has more windy coasts than elsewhere in the world, and especially Asia. Parts of these higher fluxes may have resulted from higher wind speed. As mentioned above, the wind potential is a quadratic function of wind speed, as is the 1992 Wanninkhof air-sea CO_2 exchange equation. It is important to point out, however, that the water turbulence is an importance factor for gas transfer velocity in low wind speed regions but little data is available. We have compared the Wanninkhof (1992) quadratic equation ($k_{660} = 0.31 \times U_{10}^2$) with other equations such as Raymond and Cole (2001), Borges et al. (2004), Ho et al. (2011), and Jiang et al. (2008a). Using Wanninkhof's (1992) quadratic equation may underestimate flux, although the value is similar with Ho et al. (2011) at low wind speed ($< 5m\ s^{-1}$). Note that there is no theoretical basis for the above equations as most are based on curve fitting techniques. Since we do not have data to show which equation is the best we have chosen the Wanninkhof quadratic equation which most references we cited used. Due to the fact that using different air-sea exchange equations results in large uncertainties, and that there is no universally accepted equation the above conclusion can only be deemed preliminary. The mean pCO_2 of European estuaries is roughly 1600 μatm, whereas that of Asian estuaries is much higher, around 4000 μatm. Yet, the mean wind speed on European coasts is approximately $4m\ s^{-1}$, compared with about $1.6m\ s^{-1}$ on Asian coasts. The resulting CO_2 fluxes for European estuaries average about $16.9 molC\ \ m^{-2}\ \ yr^{-1}$ vs. a much lower $8.1 molC\ m^{-2}\ yr^{-1}$ for Asian estuaries (Table 3; Fig. 6) despite their higher pCO_2.

It would be interesting to compare the latest estuary CO_2 flux with other riverine/terrestrial carbon fluxes, such as DOC/POC etc. That may give us some hints on how the organic carbon may be processed in estuaries. In the same token, putting the shelf CO_2 flux in the context of other carbon fluxes would also be useful. Although different people may prefer different gas transfer velocity constant (k) parameterization, it is generally viewed that open ocean k constants, such as Wanninkhof 1992, cannot simply be applied to estuaries. There are quite a few k parameterizations that can be used for estuaries. I think it is necessary that this is reflected in the estuary flux calculations. For the shelf waters, newer k equations may be more desirable (e.g. Wanninkhof et at. 2009; Ho et al 2011).

Reply:Thanks for these suggestions. We have now added some discussion in the text as follows:

The outgassing of CO_2 in global estuaries is $0.094 PgC\ yr^{-1}$, and is about 31% of the global riverine organic carbon flux (Seitzinger et al., 2010). This compares with the 48% of organic carbon released as CO_2 from estuaries and inland waters (Tranvik et al., 2009).

We also have added the method of calculating pCO_2 flux (new Table 6) and modified the text as follows:

Data are available from 87 continental shelves (Table 5 and Fig. 8). The method used to calculate the flux, and sources of the gas exchange coefficient and wind speed are listed in Table 6. Similar with the case for estuaries, different pCO_2 flux methods and gas transfer velocities also cause disparity in the flux estimations in coastal regions. For instance, Jiang et al. (2008b) pointed out that the average standard deviation of fluxes based on different gas transfer velocity equations reaches 14%. The available data for 87 estuaries are compartmentalized into 43 regions based on the definition of Laruelle et al. (2013) then the numerically

averaged CO_2 flux per unit area is calculated. For two regions without data, the mean flux for the similar classification region is used (Table 3).

Detailed comments:

1. In abstract, p5042 L4, '. . .negative flux indicates that the water is losing CO_2 to the atmosphere'? Looks like the sign of CO_2 flux numbers is the opposite as what defined here. Ocean CO_2 sink usually is defined as the negative flux. This should be consistent throughout the paper.

Reply:Thanks for reminding but this special issue has unified the CO_2 sink as negative flux. We have checked all signs again.

2. P5046, L1, should be 'However'.

Reply:Thanks.

3. P5046, L4-5, more recent references?

Reply:We have modified the text as follows:

Further, the exact extent of speciation changes between the organic and inorganic or dissolved and particulate carbon in the estuaries, and how much of each of these forms of carbon actually enters the oceans are yet unknown (Woodwell et al., 1973; Raymond and Bauer, 2000; Wiegner and Seitzinger, 2001; Cai, 2011; Maher and Eyre, 2011).

4. P5046, 2nd paragraph. Although global models for coastal CO_2 fluxes are not yet sufficient, but regional models are available, and more successful. This should be acknowledged with some references.

Reply:We have revised the paragraph as follows:

Since the above complex and conflicting factors influence the pCO_2 of estuarine and shelf waters, the air-sea exchanges of CO_2 in these waters globally can not yet be estimated by models although regional models have been attempted (Hofmann et al., 2011; Maher and Eyre, 2012; Wakelin et al., 2012). As a result, field data are still required. Determinations of the air-sea flux of CO_2 in the world's estuaries and continental shelves, based on direct measurements, are presented below. Data from the literature and some unpublished data from C.T.A. Chen are tabulated. Data for upper, mid and lower estuaries are compared. Seasonal and latitudinal variations are discussed and the global flux is presented. Data concerning continental shelves are also considered with reference to season and latitude before the global flux is determined.

5. P5048, L12, again, 'negative' sign here?

Reply:Thanks. It should have been a "positive" sign.

6. P5051, L11-13. Please check the numbers. I don't see Arctic estuaries equal the total areas of the estuaries around the Atlantic and Indian Ocean in Fig. 7.

Reply:These area data are published by Laruelle et al., 2013 (Table 3).

7. P5052, L12-24. Looks like Fig 11 is referred here? But there is no mention of Fig. 11. Please check.

Reply:This paragraph indeed mentions Fig. 11. We have now modified our figure captions.

8. P5052, L4, should be moved to the early part of the paper, defining flux signs.

Reply:Thanks. We think it is better to remind the readers the convention used here. The new paragraph is as follows:

Figure 9 displays a histogram of the reported daily CO_2 fluxes in different seasons and the annual flux for the world's continental shelves. Respiration rates are higher in summer and fall than in winter and spring (Hopkinson, 1985;Hopkinson, 1988;Griffith et al., 1990;Hopkinson and Smith, 2005;Jiang et al., 2010). However, as with estuaries, no seasonality of the numerical averaged flux per unit area on continental shelves is evident, and the values fall between -4.0 and $-5.5 mmolC\ m^{-2}\ d^{-1}$, except in autumn, when the flux is only $-0.5 mmolCm^{-2}\ d^{-1}$. A negative value indicates that the shelves absorb CO_2. The numerically averaged annual mean air-to-sea flux is $-1.09 \pm 2.9 molC\ m^{-2}\ yr^{-1}$. Multiplying this value by the total global area of the shelves yields a global flux of $-0.40 PgC\ yr^{-1}$, which is slightly less than the published value (Table 7).

9. P5054, L18, -0.3 PgC? Or 0.3?

Reply: It should be $0.3 PgC\ yr^{-1}$ organic carbon.

10. P5054, L21-22, need references here.

Reply: We have modified the text as follows:

As indicated above, a significant fraction of the export is decomposed in the estuaries and does not reach the shelves (Hofmann et al., 2011; Chen et al., 2012).

11. P5056, L3, 'warmer' or colder?

Reply: The sentence is deleted.

12. P5056, section 5, Future changes in carbon fluxes. This discussion is somewhat weak. I would like to see what different drivers might change CO_2 fluxes. Only temp and weathering are discussed a bit, without much implication. Other factors may also need to be discussed, such as decrease in buffering capacity, changes in biological production, eutrophication, among others.

Reply:Thanks for the opinion. We have added some discussion in the text as follows:

Increasing air temperature (Belkin, 2009) tends to increase precipitation and continental runoff. These processes enhanced rock weathering during the last century (Probst et al., 1994). Intuitively, this fact suggests an increased export of carbon by rivers but whether the global river runoff has increased is uncertain (Dai et al., 2011;Syed et al., 2010). The construction of dams around the world has caused a substantial fraction of exported sediment to be impounded in recent decades (Chen, 2002;Syvitski et al., 2005). A related issue is that global warming is warming the oceans as well. The global mean sea surface temperature has reportedly risen by 0.67°C over the last century (IPCC, 2007;Trenberth et al., 2007). The most rapid warming, two to four times the global average of 0.177°C per decade between 1981 and 2005, has been observed in the land-locked or semi-enclosed European and East Asian Seas, including the Baltic, North, Black, Japan and East China Seas as well as over the Newfoundland-Labrador Shelf (Belkin, 2009). The thermodynamics of seawater dictates that for each °C rise in temperature, the pCO_2 increases by 4%, or approximately 14 μatm. This fact would compensate for some of the increase in CO_2 in the atmosphere, which is of the order of 18 μatm per decade. With increasing atmospheric CO_2 concentration, the pCO_2 difference between the air and the shelf seawater will become larger. This is to the advantage of absorbing atmospheric CO_2 in coastal seas, and even some CO_2 emitting regions may start to absorb CO_2. A related issue is that the eutrophicated coastal area is growing

due to human activities such as excessive nutrient inputs and enhanced soil erosion on land (Brush, 2009; Smith and Schindler, 2009). Values of pH in the coastal seawater will drop faster than in the open ocean because decomposition of terrestrial organic material increases the total alkalinity but reduces the buffering capacity (Chen et al., 1982; Cai et al., 2011). Further, certain species of phytoplankton may grow better in a high CO_2 environment (Riebesell and Tortell, 2011), hence deterring the increasing trend of atmospheric CO_2 in general. These effects, however, are beyond the scope of this study.

Table 3. Please check the sign of the fluxes for consistency.

Reply:We have checked these signs again.

Fig. 2. Lack of vertical labels. Why is there a mismatch of n between the upper and lower panel? Should be the same number of observations listed? The caption needs to be improved.

Reply:The vertical label and number mean how many estuaries are collected. The numbers for the upper and lower estuaries do not match because of the limitation of published data. For instance, sampling frequently did not include whole estuaries.

Figs. 6, 7, 11, 12. Need to define abbreviations.

Reply:Thanks for the suggestion, we have now modified the figure captions as follows: **Fig. 6. Annual CO_2 flux (a), average CO_2 flux per unit area (b), total surface area (c), and percentage of total CO_2 flux (d) from estuaries in each continent. Numbers in parentheses indicate the number of estuaries studied. Fig.7. Annual CO_2 flux (a), average CO_2 flux per unit area (b), total surface area (c), and percentage of total CO_2 flux (d) from estuaries of each ocean. Numbers in**

parentheses indicate the number of estuaries studied. Fig.11. Annual CO_2 flux (a), average CO_2 flux per unit area (b), total surface area (c), and percentage of total CO_2 flux (d) from continental shelves in different continents. Numbers in parentheses indicate the number of shelves studied. Fig.12. Annual CO_2 flux (a), average CO_2 flux per unit area (b), total surface area (c), and percentage of total CO_2 flux (d) from continental shelves in different oceans. Numbers in parentheses indicate the number of shelves studied.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/10/C4279/2013/bgd-10-C4279-2013-supplement.pdf

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